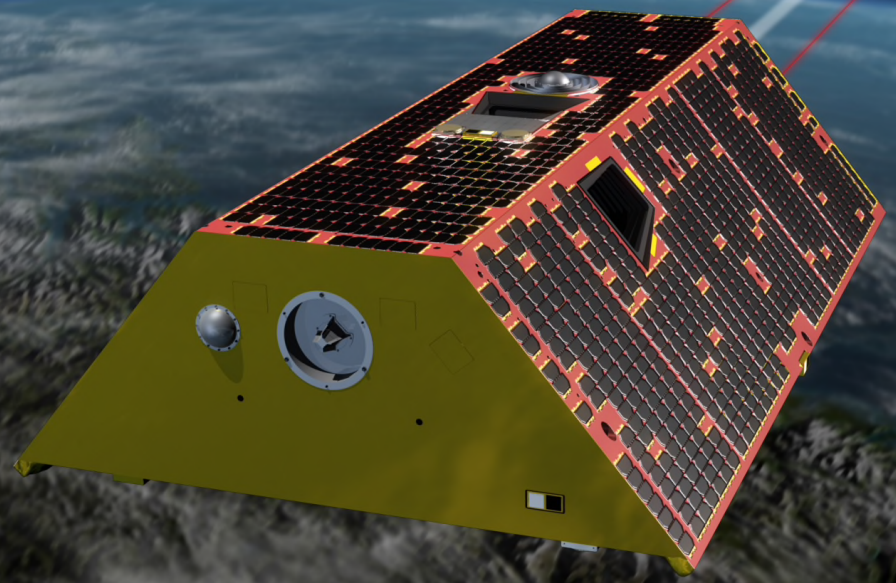
LISA technology demonstration and flight experience from GRACE Follow-On

Brent Ware, for the
US and German LRI collaboration

NASA/Jet Propulsion Laboratory,
California Institute of Technology

AAS 2020



GRACE-FO Partnership

LRI Design & Management

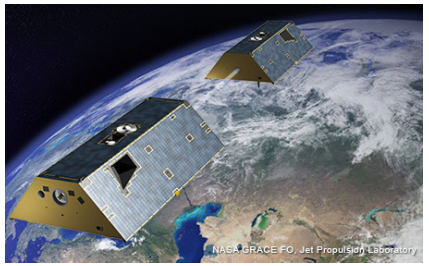
LRI implementation

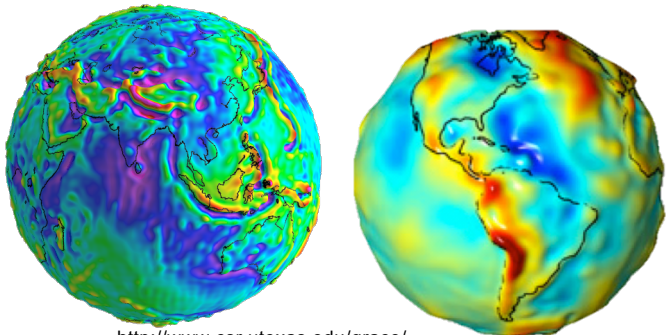
SpaceTech Immenstaad

GRACE and GRACE Follow-On

- **Gravity Recovery and Climate Experiment**
  GRACE (since 2002 to 2017):
  - NASA/German Research Centre for Geosciences (GFZ) partnership
  - 220km separation measurement of 2 spacecraft by dual microwave links
  - Spacecraft separation + location (GPS) yield orbit
    Orbit determines gravity map
  - Gravity map evolution over months and years
    Insight into earth systems & effects of climate change
    Really impressive science!

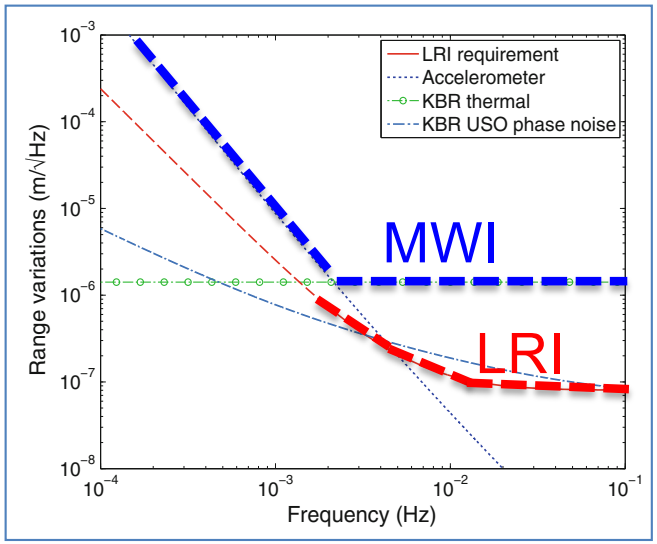
- **GRACE Follow-On (Launched May 22, 2018) will continue science**
  - Microwave Ranging Instrument (MWI) and Accelerometer similar to GRACE
  - ***Tech-Demo for All-Optical GRACE*** *: Laser Ranging Interferometer (LRI)*
    First inter-spacecraft interferometer
  - ***Long running development Astrophysics (LISA) and Earth Science (GRACE 2) funnding***





http://www.csr.utexas.edu/grace/

GRACE Follow-On Requirement Noise Levels



B. Sheard et al, J Geod (2012)

The Laser Ranging Interferometer (LRI)

The LRI is a partnership between the US and Germany

US: Stabilized laser and Metrology

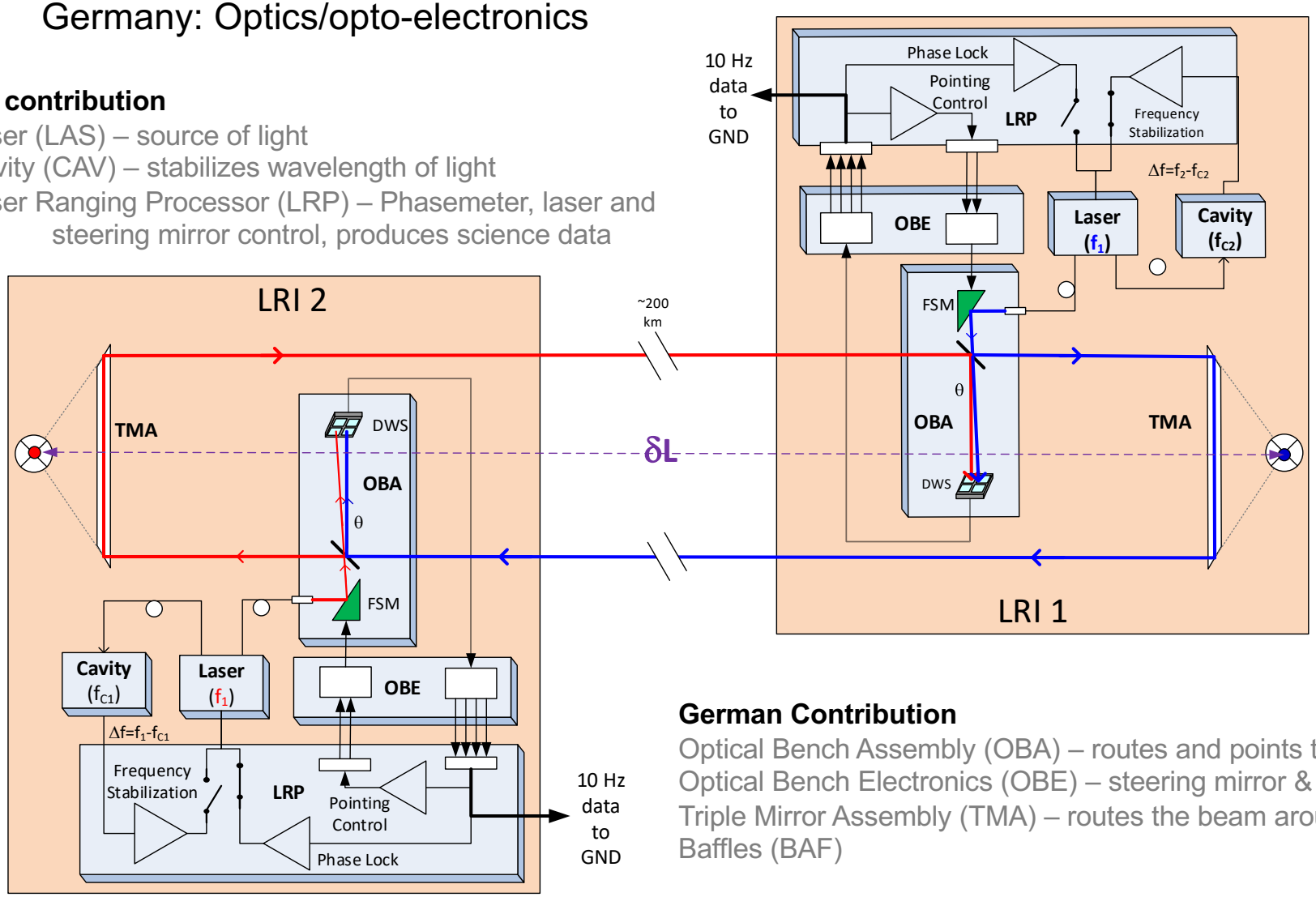
Germany: Optics/opto-electronics

US contribution

Laser (LAS) – source of light

Cavity (CAV) – stabilizes wavelength of light

Laser Ranging Processor (LRP) – Phasemeter, laser and steering mirror control, produces science data



German Contribution

Optical Bench Assembly (OBA) – routes and points the beam

Optical Bench Electronics (OBE) – steering mirror & detector drivers

Triple Mirror Assembly (TMA) – routes the beam around MWI

Baffles (BAF)

Comparison of the LRI and LISA

Parameter	LRI	LISA
Measurement Noise	80 nm/rtHz	20 pm/rtHz
Shot Noise	*0.01 nm/Hz$^{1/2}$*	*7 pm/Hz$^{1/2}$*
Photoreceiver Noise (but note carrier to noise density requirement)	*1 nm/Hz$^{1/2}$*	*3 pm/Hz$^{1/2}$*
Phasemeter Noise	*1 nm/Hz$^{1/2}$*	*1 pm/Hz$^{1/2}$*
Optical Pathlength Noise	*30 nm/Hz$^{1/2}$*	*3 pm/Hz$^{1/2}$*
Laser Frequency Noise	*35 nm/Hz$^{1/2}$*	*1 pm/Hz$^{1/2}$*
USO Noise	*1 nm/Hz$^{1/2}$*	*1 pm/Hz$^{1/2}$*
Satellite Separation	**170..270 km**	**5 million km**
Satellite Relative Velocity	**≤±3m/s**	**≤±15m/s**
Wavelength	**1.064 × 10^{-6}m**	**1.064 × 10^{-6}m**
Phase Precision	**10^{-3} cycles Hz$^{-1/2}$**	**1 microcycle Hz$^{-1/2}$**
Nominal Carrier-to-noise Density	**≥ 75 dB-Hz (single phasemeter channel)**	**≥ 75 dB-Hz (single phasemeter channel)**
IF Signal Frequency	**4–16 MHz**	**2–18 MHz**
IF Signal Dynamics (@ 1 Hz)		
Before Frequency Stabilization	*5000 Hz Hz$^{-1/2}$*	*5000 Hz Hz$^{-1/2}$*
After Frequency Stabilization	*30 Hz Hz$^{-1/2}$*	*300 Hz Hz$^{-1/2}$*
Science Bandwidth	2mHz – 100mHz	0.1 mHz – 1Hz
Rx Optical Power	**79–625 pW**	**80 pW**
Number of Phase Channels	**4**	**44+**
ADC Clocking Rate	**38.656 MHz**	**50 MhZ**
Time Coordination	**GPS (laser ranging code could be used)**	**Laser ranging code**
Laser Phase Locking	**Required**	**Required**
Pointing Information	**Wavefront sensing**	**Wavefront sensing**
Pointing Precision	*1 urad/Hz$^{-1/2}$*	*80 nrad/Hz$^{-1/2}$*

NASA Technology Development Roadmap for a Future Gravitational-Wave Mission

LRI design based on LISA technology and capabilities.

- **Designed by LISA scientists and technologists (NASA and Germany)**
- LRI top level precision relaxed
- Tighter laser stability requirement

Similar:

- Doppler shift and IF signal
- Received optical power
- mHz-band science signal frequency
- Link architecture: stabilized master and offset phase-locked slave
- Photoreceiver properties

Both LRI and LISA require:

- Low light power tracking
- Differential wavefront sensing
- 5 degree of freedom acquisition

LRI is providing technology demonstration for LISA and represents a huge step towards LISA

LRI is demonstrating the first inter-spacecraft interferometer

GRACE Follow-On Spacecraft

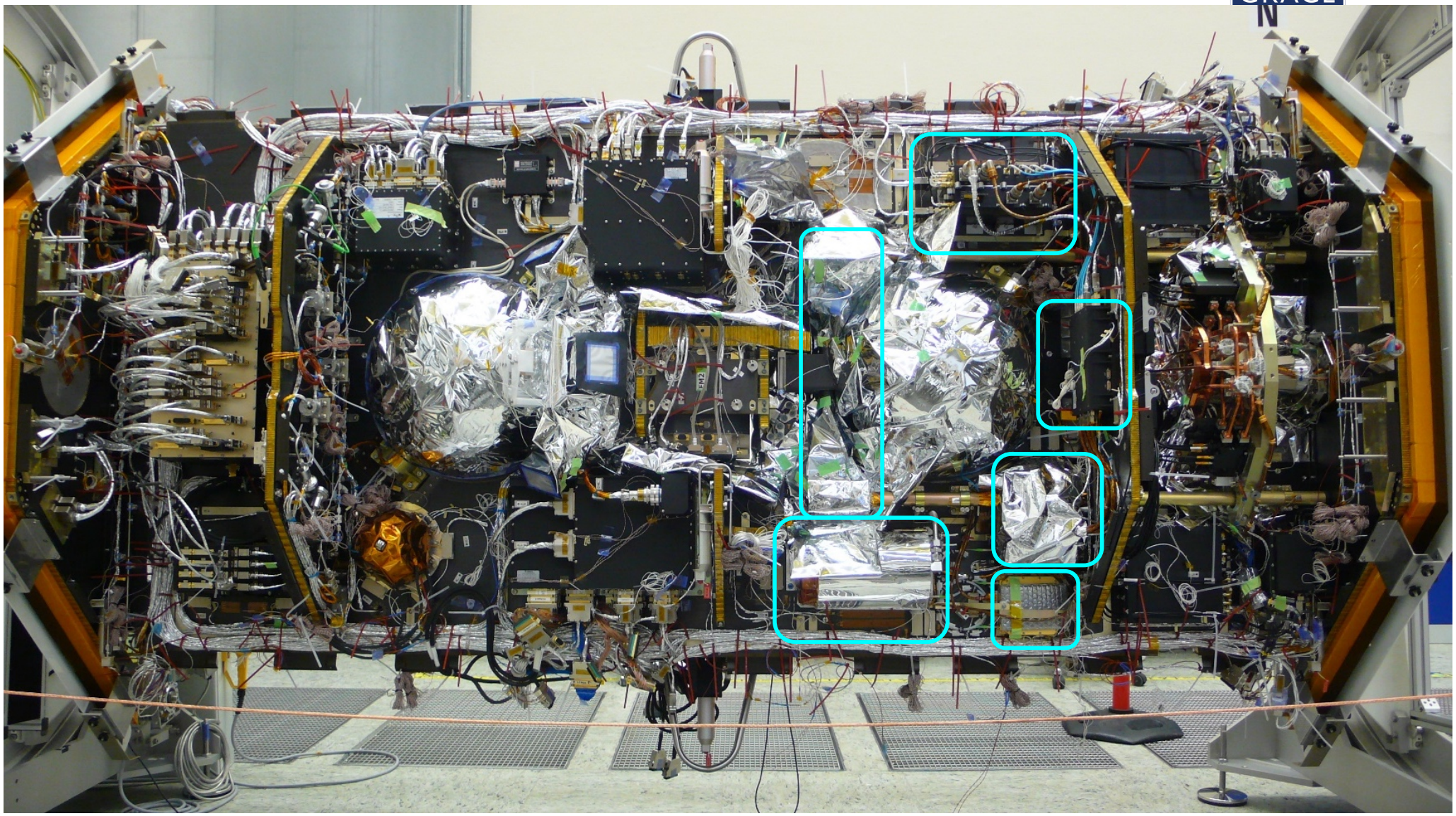
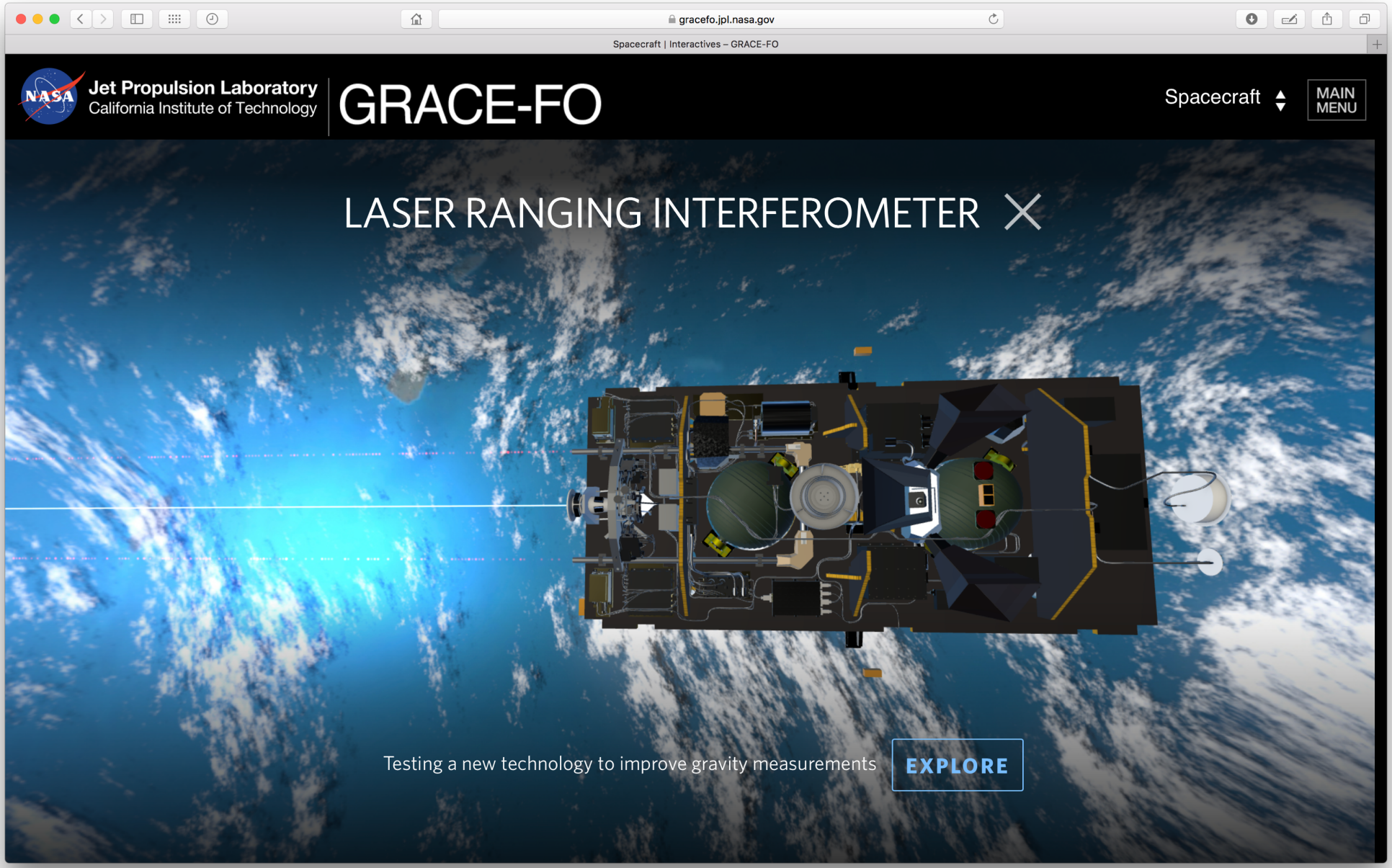
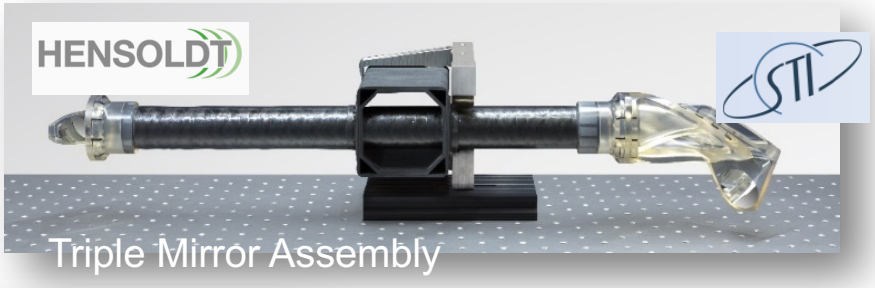


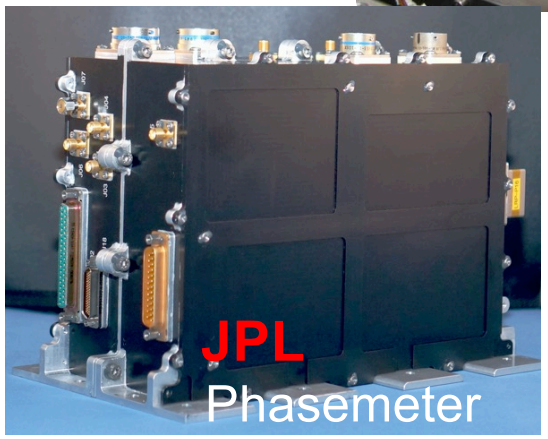
Image Courtesy of Airbus and JPL

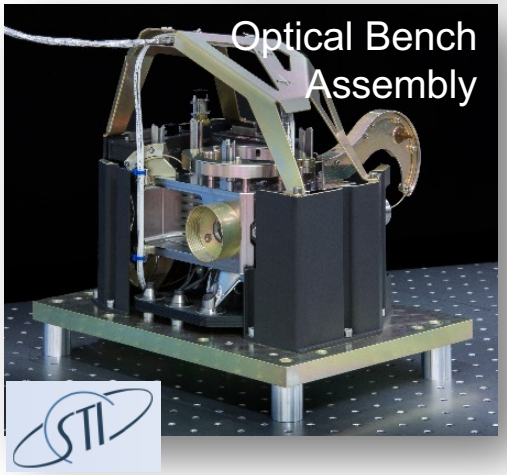
https://gracefo.jpl.nasa.gov/interactives/spacecraft/

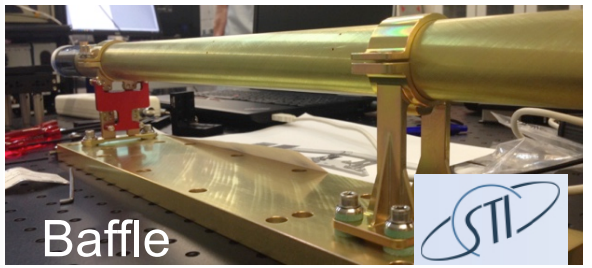


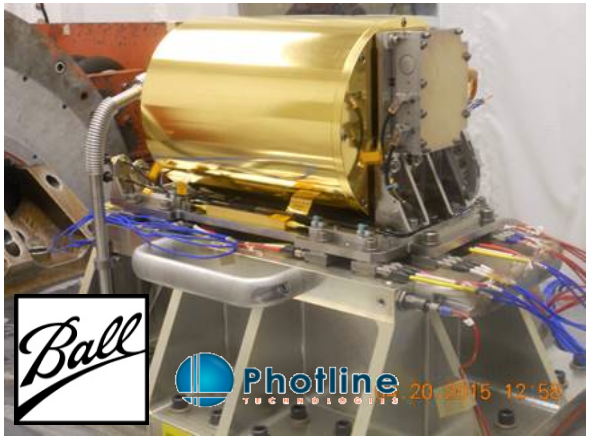
LRI Flight Components



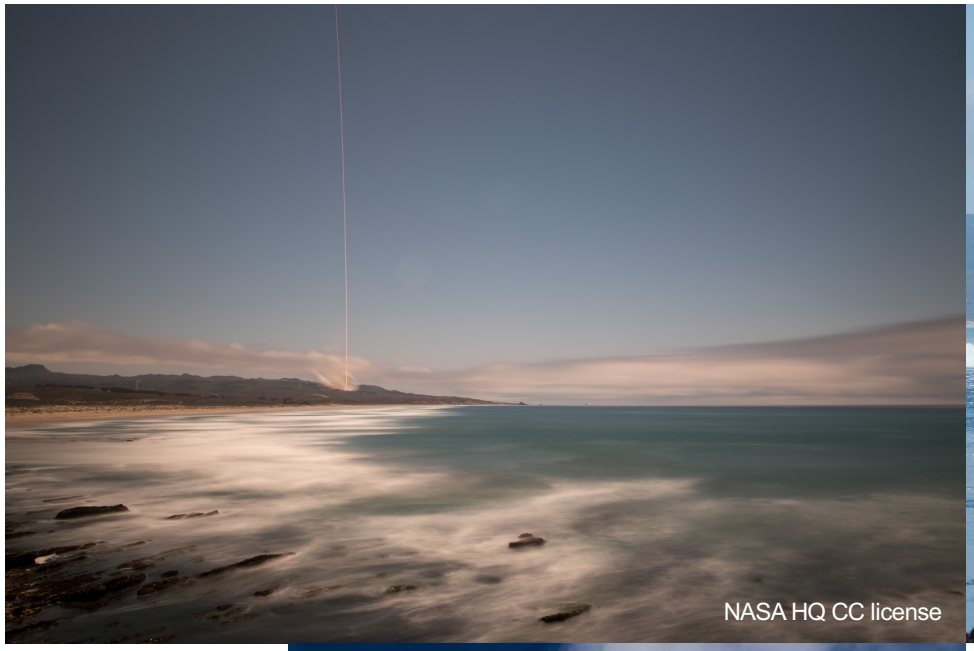








Optical Bench Electronics



SpaceX @SpaceX · 8h
Successful deployment of GRACE-FO satellites.
39 518 3.9K

SpaceX @SpaceX · 8h
Second stage engine cutoff confirmed.
21 185 2.1K

SpaceX @SpaceX · 8h
Fairing has deployed.
48 260 2.7K

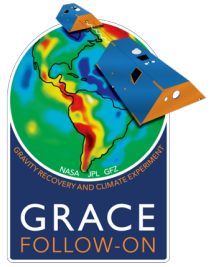
SpaceX @SpaceX · 8h
Main engine cutoff and stage separation confirmed. Second stage engine burn underway.
20 219 2.3K

SpaceX @SpaceX · 8h
Liftoff!
114 1.1K 8.7K

SpaceX @SpaceX · 8h
T-60 seconds until launch → spacex.com/webcast

Launch video: https://wolke7.aei.mpg.de/s/YKgHDGJwpLrXKYr

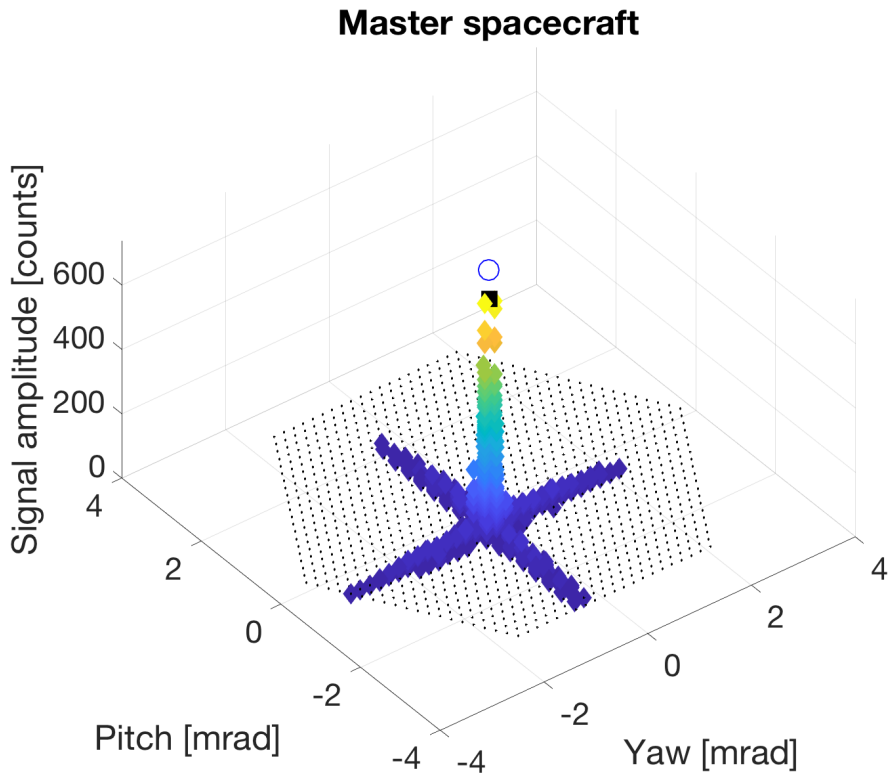
LRI Turn on and start of commissioning

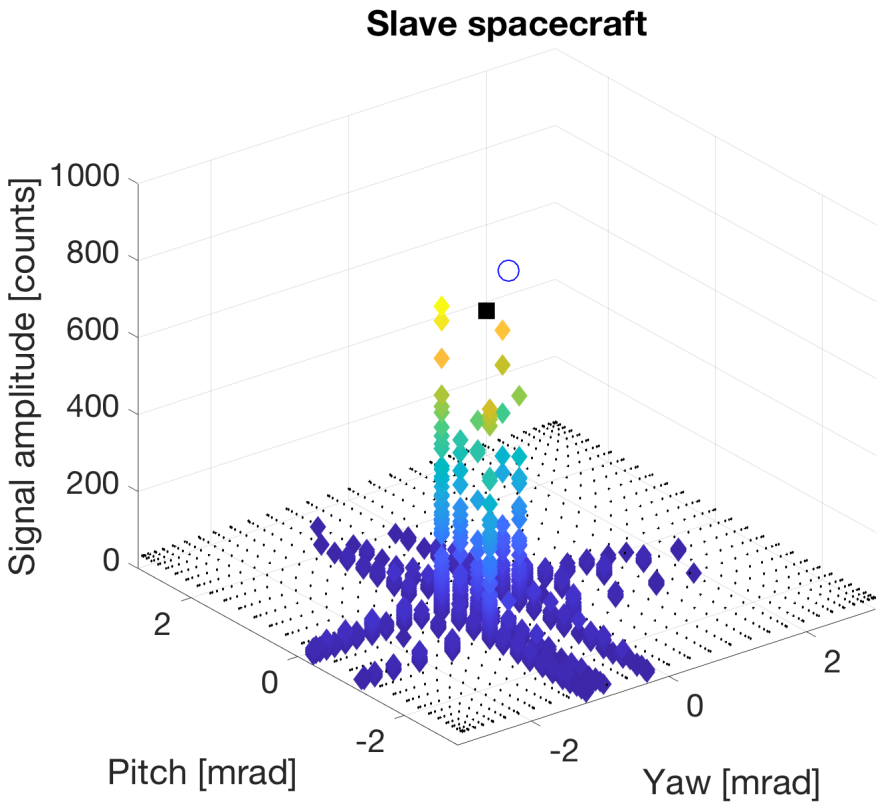


- LRI Powered on June 11th (spacecraft 1) and June 12th (spacecraft 2)
- Single spacecraft Checkout overnight showed the Laser, Cavity, Optical Bench, and Control electronics all checked out well
  - The phasemeter and Triple Mirror Assembly could not be checked until the link was formed
- The Open Loop Search Scan ran on June 13th
  - Nine hour spatial scan
  - Looking for a heterodyne beatnote (unlike LISA acquisition which has a dedicated CCD sensor)
  - **Inter-spacecraft signal detected with high SNR!**
  - > this gives: where to point the steering mirrors and laser frequency settings
- Upload of new parameters on June 14th

Inter-spacecraft laser interferometer link acquired autonomously on the very first acquisition attempt

Open Loop Scan results

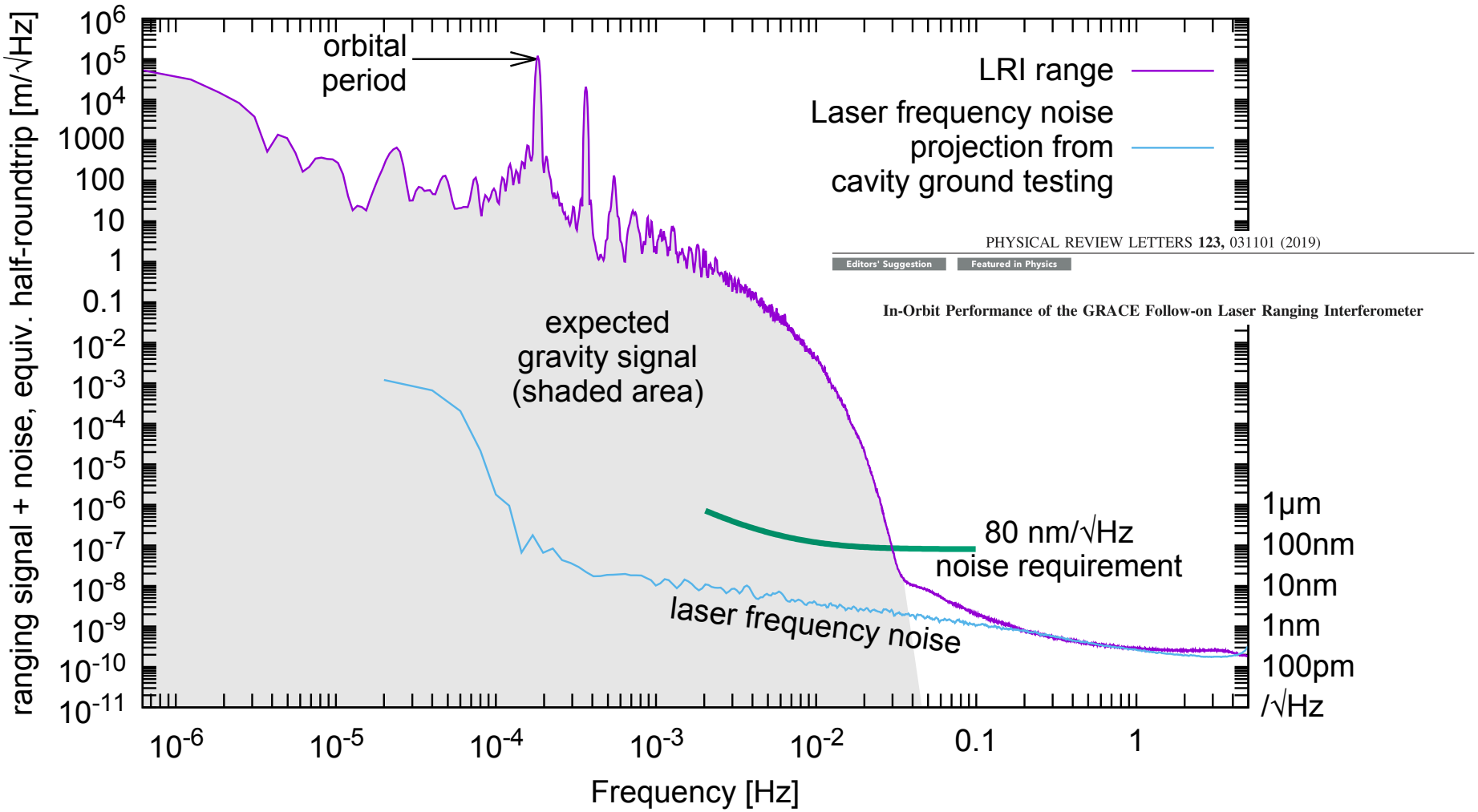




First downlink: beautiful evidence of heterodyne signal

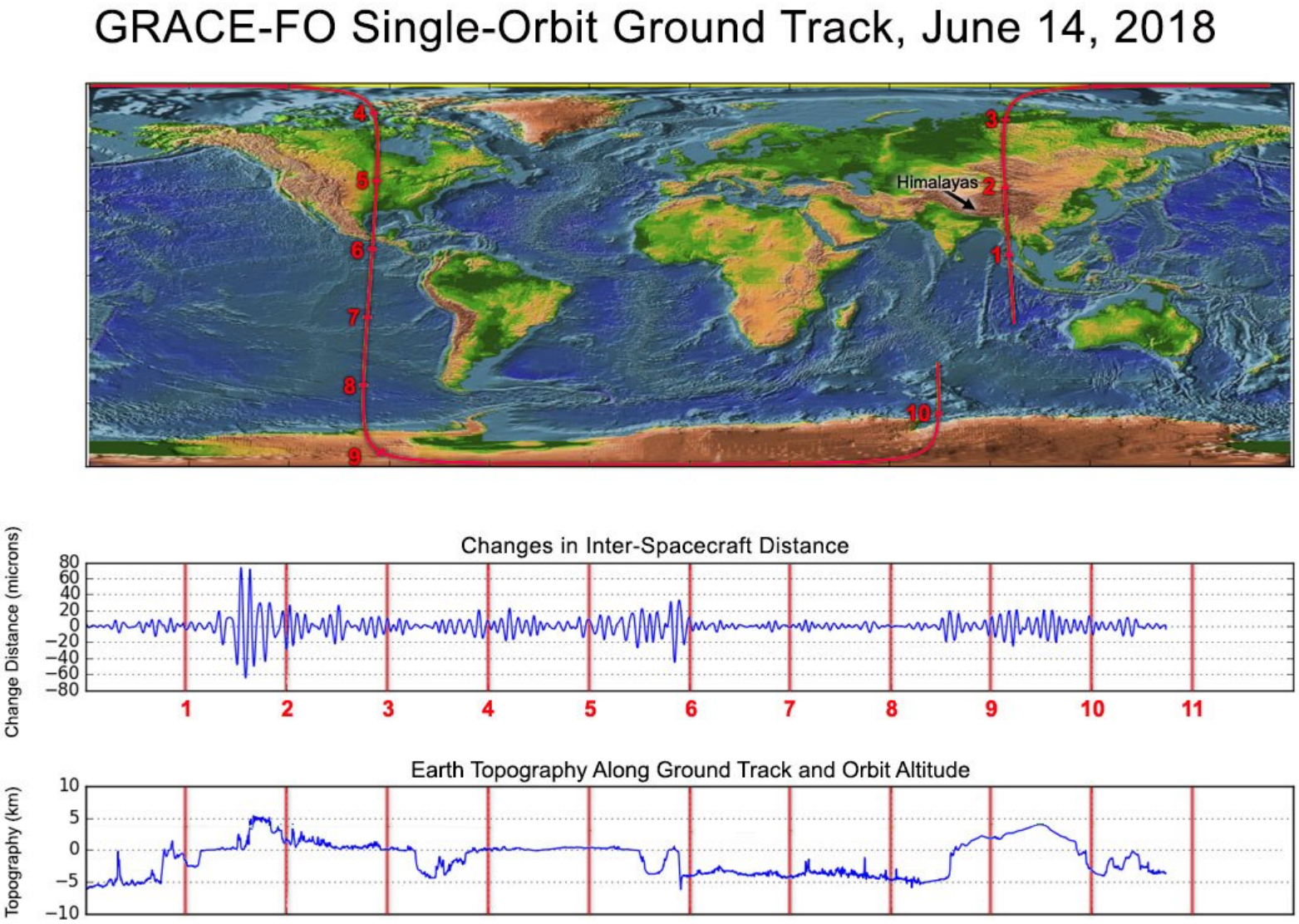
Interferometer performance better than requirements above gravity signal band

- LRI has been tracking for more than a year
- 2500 orbits
- No unexpected dropouts from continuous interferometry.
- Continuous tracking of large spacecraft tilts based on Differential Wavefront Sensing, four degrees of freedom



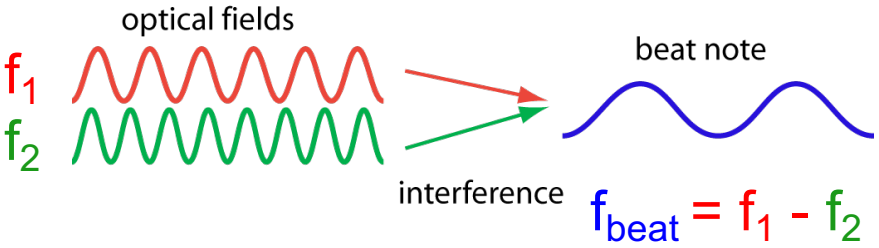
Signal success: Gravity measured

Filtered interferometer signal correlates with topography.

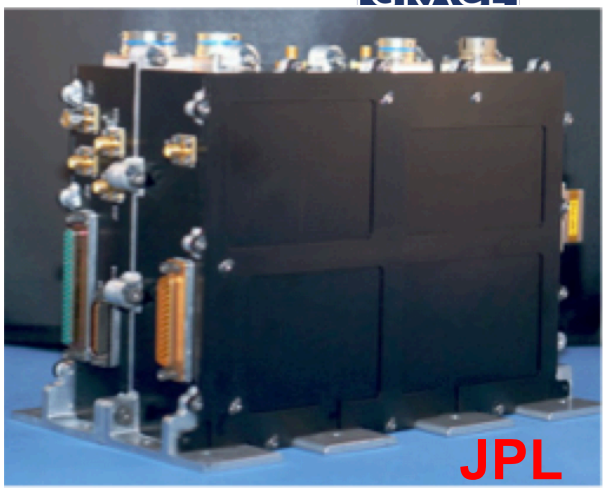


https://gracefo.jpl.nasa.gov/news/138/first-laser-light-for-grace-follow-on/

LRI Phasemeter aka Laser Ranging Processor (LRP)



The phasemeter measures the science signal as a mHz phase modulation on a MHz beat signal.



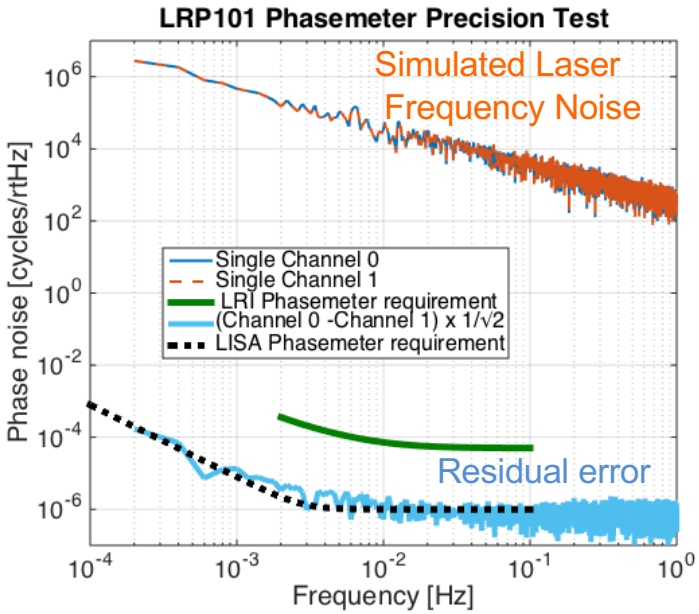
LRI Flight model Phasemeter

LRP developed at JPL, based on the LISA Phasemeter

The LRP implements the LISA phase tracking and frequency control algorithms, including:

- Phase tracking
- Differential wavefront sensing (and control)
- Laser Phase Locking
- Laser frequency stabilization

- Has only 4 input channels (vs 34 for LISA)
- Relaxed precision requirement, but ~ LISA performance

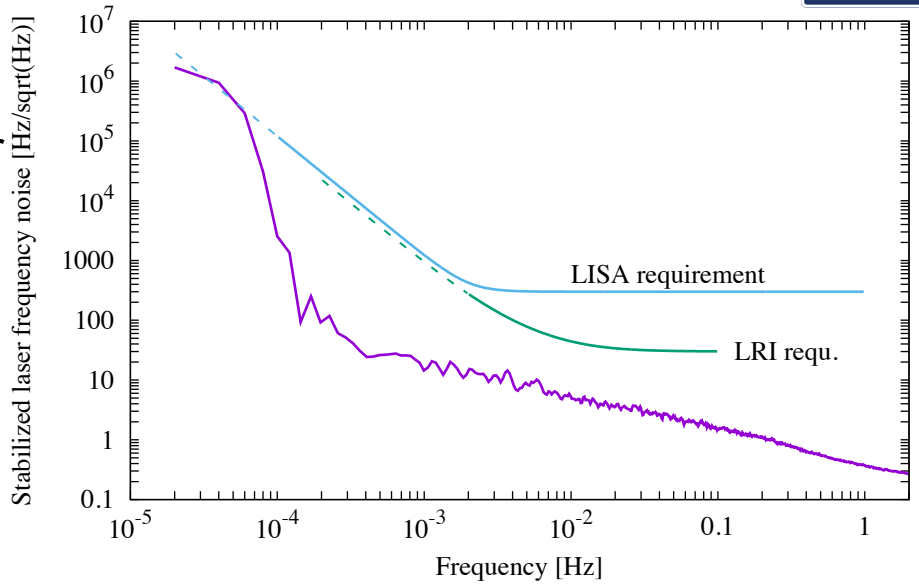


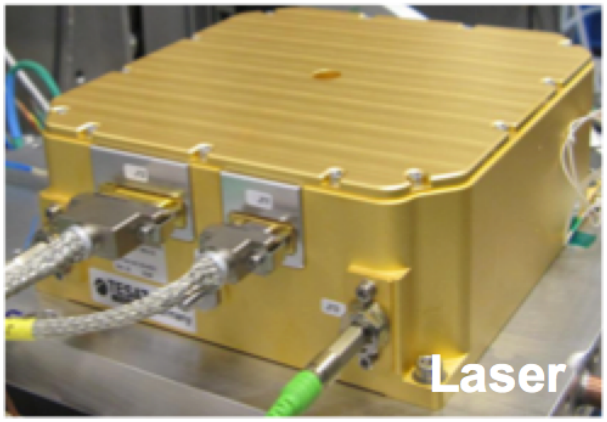
LRI Laser Frequency Stabilization: Flight Phasemeter, Flight Cavity, and Flight Laser

- Similar to Laser on LISA Pathfinder:
  - Wavelength: 1064 nm
  - Nd:YAG Non-Planar Ring Oscillator
- Laser output power: 25 mW

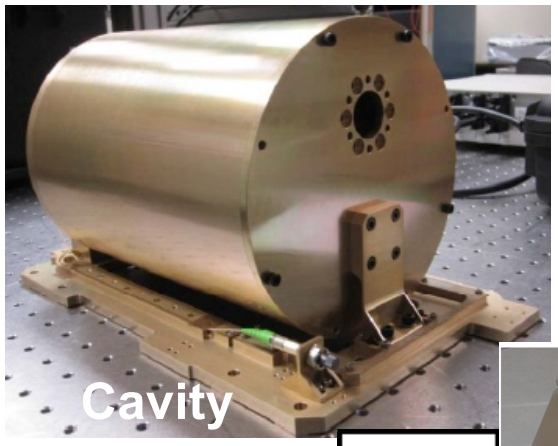
- NASA Earth Science developed Cavity
  - IIP: Ball Aerospace/JPL
- LRP implements laser frequency control (locks laser to cavity resonance)
  - Near mirror thermal noise stability

Ball/JPL cavity flying on GRACE Follow-On LRI
(ground test data)



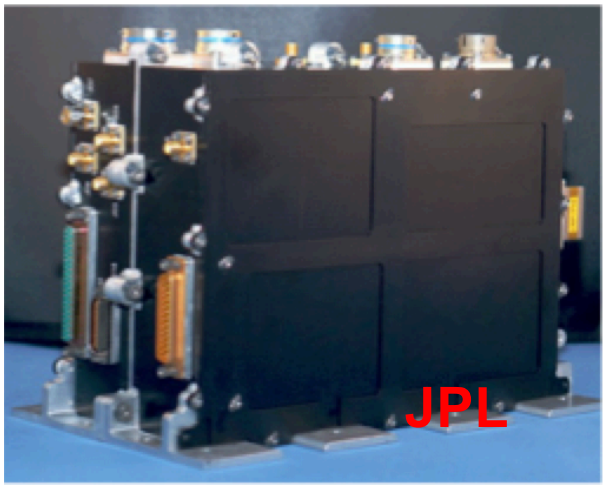


TESAT SPACECOM



Ball

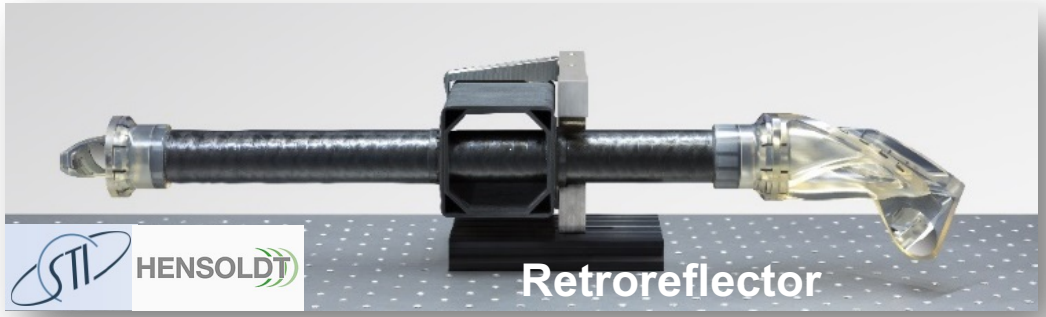
Flight phasemeter controlling flight laser to flight cavity, x2

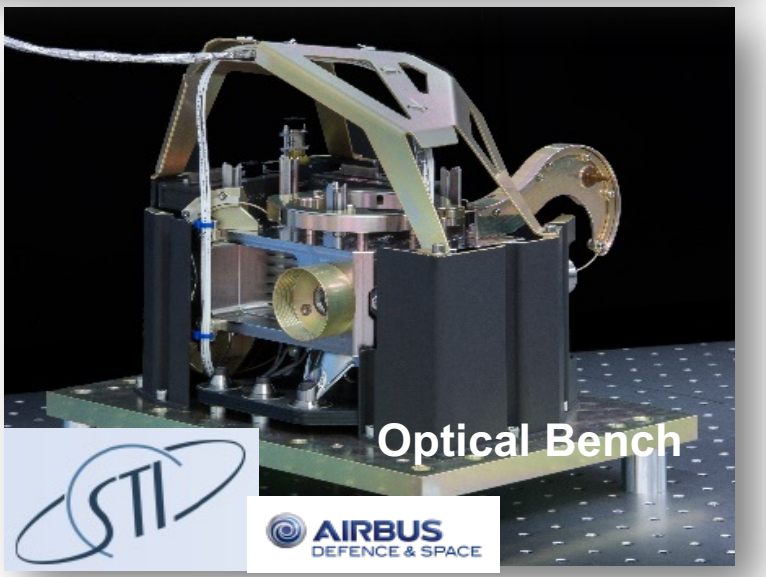


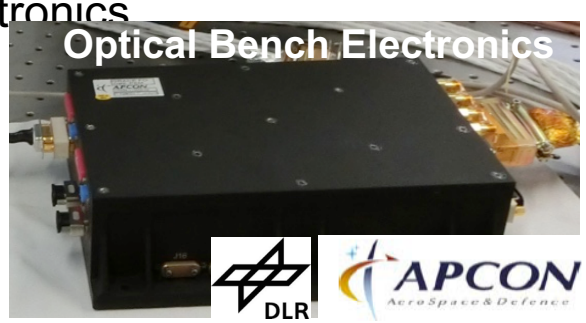
LRI : Beam Manipulation and heterodyne signal detection
Flight Optical Bench, Flight Retroreflector and Baffles

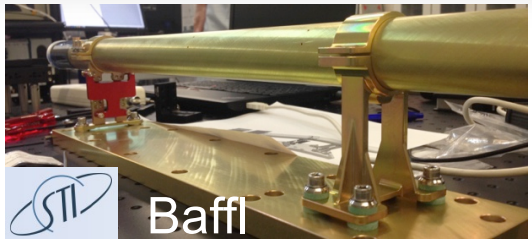
- Triple Mirror Assembly (TMA)
  - 60 cm lateral displacement between in & outgoing beam
  - lightweight CFRP structure + Zerodur mirrors

- Optical Bench Sub-System (OBS)
  - Titanium structure
  - Beam compressor / imaging system
  - Two hot redundant quadrant photoreceivers
    - InGaAs QPDs with 1 mm diameter
    - Bandwidth: 4...16 MHz
- External front end electronics







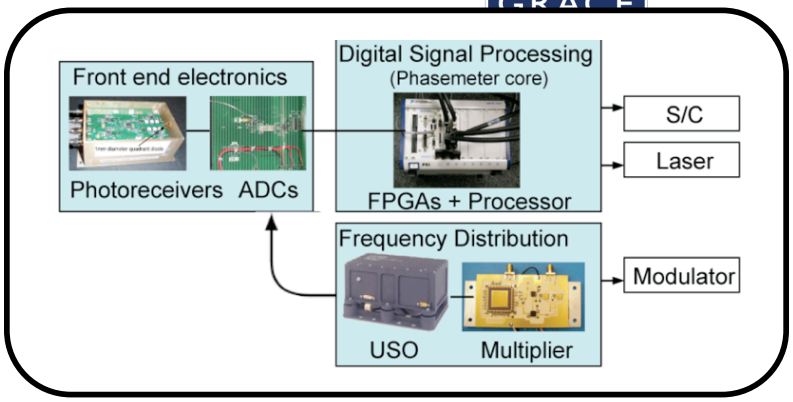


Time Delay Interferometry with the LISA Phasemeter

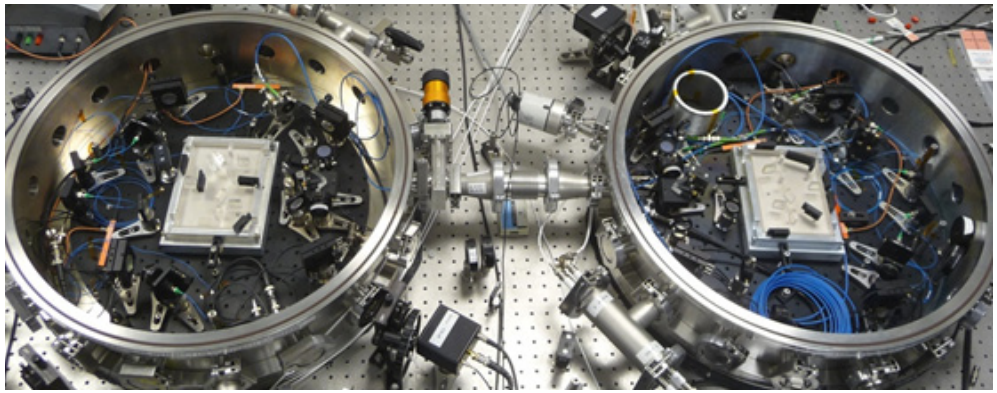
JPL LISA interferometer testbed used to demonstrate phase measurement system components and system performance to TRL 4

- Retired the highest LISA phase measurement risk[1]
- Frequency noise removal to interferometer displacement limit
- Clock Tone Transfer via GHz phase modulation
- Interpolation of data streams onto common time-base

Currently, testing the LRP (LRI phasemeter) on the JPL LISA Interferometry testbed.



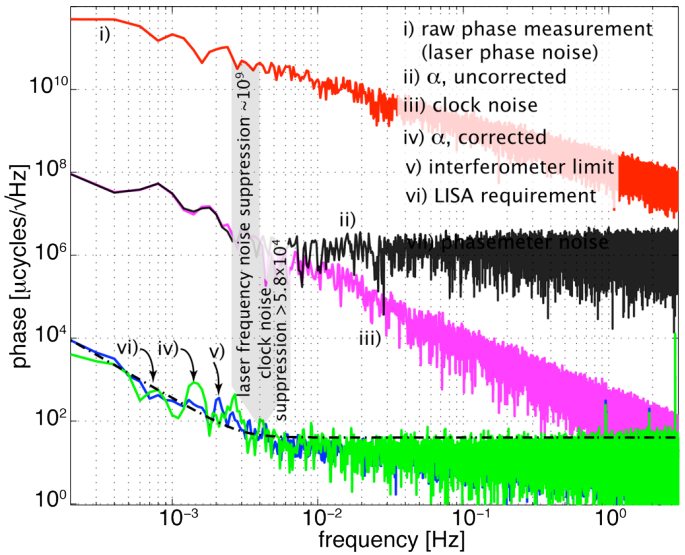
JPL LISA Interferometry testbed



PRL 104, 211103 (2010) PHYSICAL REVIEW LETTERS week ending 28 MAY 2010

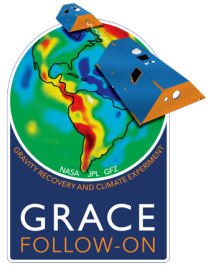
Experimental Demonstration of Time-Delay Interferometry for the Laser Interferometer Space Antenna

Glenn de Vine,* Brent Ware, Kirk McKenzie, Robert E. Spero, William M. Klipstein, and Daniel A. Shaddock†
Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, USA
(Received 1 April 2010; published 27 May 2010)



[1] NASA's LISA Technology Development Plan V 1.0 (2005)

Summary



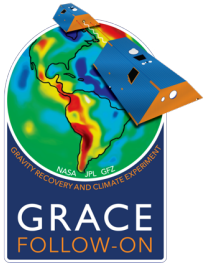
- GRACE Follow-On Laser Ranging Interferometer (LRI), the first inter-spacecraft laser interferometer has been successfully operating since powering up in June, 2018.

- The LRI is a US-German partnership.
  - Effective collaboration on design, noise budgets, acquisition technique, and test planning and execution
  - US: Phasemeter, laser and cavity
  - Germany: Optics/opto-electronics

- Instrument design and many technology elements from LISA development

- The LRI mission parameters have many similarities to LISA
  - Makes the LRI a relevant technology demonstrator for LISA
  - Increases maturity of key LISA technologies
    (US: advanced phasemeter and Optical Cavity)

US and German LRI Collaboration



Jet Propulsion Laboratory
California Institute of Technology

Adlershof
Bremen
GSOC